Strings and Particle Physics

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Questions

- What can we learn from strings for particle physics?
- Can we incorporate particle physics models within the framework of string theory?
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- Can we incorporate particle physics models within the framework of string theory?

Recent progress:

- explicit model building towards the MSSM
  - Heterotic brane world
  - local grand unification
- moduli stabilization and Susy breakdown
  - warped throats
  - modulus or mirage mediation
The road to the Standard Model

What do we want?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- no chiral exotics
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But there might be more:

- supersymmetry (SM extended to MSSM)
- neutrino masses (see-saw mechanism)

as a hint for a large mass scale around $10^{16}$ GeV
Grand Unification

SUSY-GUTs provide us with nice things like

- unified multiplets (e.g. spinors of SO(10))
- gauge coupling unification
- Yukawa unification
- neutrino see-saw mechanism

But there remain a few difficulties:

- breakdown of GUT group (large representations)
- doublet-triplet splitting problem (incomplete multiplets)
- proton stability (need for R-parity)
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Local Grand Unification

Can such things come from string theory where it is **notoriously difficult** to obtain large representations (beyond the adjoint representation of the gauge group)?
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In fact string theory gives us a variant of GUTs

- complete multiplets for fermion families
- split multiplets for gauge- and Higgs-bosons
- partial Yukawa unification

in a geometrical set-up known as local GUTs, realized in the framework of the “heterotic braneworld”.

(Förste, HPN, Vaudrevange, Wingertter, 2004)
Localization

Quarks, Leptons and Higgs fields can be localized:

- in the Bulk \((d = 10\) untwisted sector\)
- on 3-Branes \((d = 4\) twisted sector fixed points\)
- on 5-Branes \((d = 6\) twisted sector fixed tori\)
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but there is also a “localization” of gauge fields

- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

Observed 4-dimensional gauge group is common subgroup of the various localized gauge groups!
Localized Gauge Symmetries

\[ \text{SU}(4)^2 \quad \text{SU}(6) \times \text{SU}(2) \]

SO(10)

SU(6) \times SU(2)

(Förste, HPN, Vaudrevange, Wingerter, 2004)
Standard Model Gauge Group

$\text{SU}(4)^2 \quad \text{SU}(3)^2 \quad \text{SU}(6) \times \text{SU}(2)$

$\text{SU}(4) \times \text{SU}(2)^2 \quad \text{SU}(3)^2 \quad \text{SU}(4) \times \text{SU}(2)^2$

$\text{SO}(10) \quad \text{SU}(5) \quad \text{SU}(6) \times \text{SU}(2)$

$\text{SU}(5)$
The Remnants of SO(10)

- $SO(10)$ is realized in the higher dimensional theory
- broken in $d = 4$
- coexistence of complete and incomplete multiplets
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Still there could be remnants of $SO(10)$ symmetry

- 16 of $SO(10)$ at some branes
- correct hypercharge normalization
- R-parity

that are very useful for realistic model building ...
Benchmark Scenario: $\mathbb{Z}_6$ II orbifold

- provides fixed points and fixed tori
- allows $SO(10)$ gauge group
- allows for localized 16-plets for 2 families
- $SO(10)$ broken via Wilson lines
- nontrivial hidden sector gauge group

(Kobayashi, Raby, Zhang, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)
# Selection Strategy

<table>
<thead>
<tr>
<th>criterion</th>
<th>$V^{SO(10),1}$</th>
<th>$V^{SO(10),2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>② models with 2 Wilson lines</td>
<td>22,000</td>
<td>7,800</td>
</tr>
<tr>
<td>③ SM gauge group $\subset$ SO(10)</td>
<td>3563</td>
<td>1163</td>
</tr>
<tr>
<td>④ 3 net families</td>
<td>1170</td>
<td>492</td>
</tr>
<tr>
<td>⑤ gauge coupling unification</td>
<td>528</td>
<td>234</td>
</tr>
<tr>
<td>⑥ no chiral exotics</td>
<td>128</td>
<td>90</td>
</tr>
</tbody>
</table>

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)
The road to the MSSM

The benchmark scenario leads to

- 200 models with the exact spectrum of the MSSM (absence of chiral exotics)
- local grand unification (by construction)
- gauge- and (partial) Yukawa unification
  (Raby, Wingerter, 2007)
- examples of neutrino see-saw mechanism
  (Buchmüller, Hamguchi, Lebedev, Ramos-Sanchez, Ratz, 2007)
- models with R-parity + solution to the \(\mu\)-problem
  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)
- hidden sector gaugino condensation
\[ m_{3/2} = \frac{\Lambda^3}{M_{\text{Planck}}^2} \quad \text{(with} \quad \Lambda = \mu \exp(-1/g_{\text{hidden}}^2(\mu)) \quad \text{)} \]

from hidden sector gaugino condensation

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)
Two Basic Questions

- origin of the small scale?
- stabilization of moduli?
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- origin of the small scale?
- stabilization of moduli?

Recent progress in

- moduli stabilization via fluxes in warped compactifications of Type IIB string theory
  (Dasgupta, Rajesh, Sethi, 1999; Giddings, Kachru, Polchinski, 2001)

- generalized flux compactifications of heterotic string theory
  (Becker, Becker, Dasgupta, Prokushkin, 2003; Gurrieri, Lukas, Micu, 2004)

- combined with gaugino condensates and “uplifting”
  (Kachru, Kallosh, Linde, Trivedi, 2003)
Is there a general pattern of the soft mass terms?

We have (from warped flux and gaugino condensate)

\[ W = \text{something} - \exp(-X) \]

where "something" is small and \( X \) is moderately large.
Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We have (from warped flux and gaugino condensate)

\[ W = \text{something} - \exp(-X) \]

where “something” is small and \( X \) is moderately large.

In fact in this simple scheme

\[ X \sim \log(\frac{M_{\text{Planck}}}{m_{3/2}}) \]

providing a “little” hierarchy.

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)
Mixed Modulus Anomaly Mediation

The contribution from “Modulus Mediation” is therefore suppressed by the factor

\[ X \sim \log(M_{\text{Planck}}/m_{3/2}) \]

Numerically this factor is given by: \[ X \sim 4\pi^2. \]
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Thus the contribution due to “Anomaly Mediation” (suppressed by a loop factor) becomes competitive, leading to a Mixed Modulus-Anomaly-Mediation scheme.

For reasons that will be explained later we call this scheme MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)
The little hierarchy

\[ m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\text{soft}} \]

is a generic signal of such a scheme

- moduli and gravitino are heavy
- gaugino mass spectrum is compressed

(Choi, Falkowski, HPN, Olechowski, 2005; Endo, Yamaguchi, Yoshioka, 2005;
Choi, Jeong, Okumura, 2005)

such a situation occurs if SUSY breaking is “sequestered” on a warped throat

(Kachru, McAllister, Sundrum, 2007)
Mirage Unification

Mirage Mediation provides a characteristic pattern of soft breaking terms.\(^{(Choi, Jeong, Okumura, 2005)}\)

Gaugino masses receive two contributions

\[ M_{1/2} = M_{\text{modulus}} + M_{\text{anomaly}} \]

of comparable size.

- \(M_{\text{anomaly}}\) is proportional to the \(\beta\) function, i.e. \textbf{negative} for the gluino, \textbf{positive} for the bino
- thus \(M_{\text{anomaly}}\) is non-universal below the GUT scale
Evolution of couplings

\[ \log_{10}(\mu/\text{GeV}) \]

\[ \alpha_i \]

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The Mirage Scale

\begin{align*}
M_1 &\quad \text{green dashed line} \\
M_2 &\quad \text{red line} \\
M_3 &\quad \text{blue dashed line}
\end{align*}

\[
\log_{10}(\mu/\text{GeV})
\]

\[
M_i/\text{GeV}
\]
The Mirage Scale (II)

The gaugino masses coincide above the GUT scale and at the mirage scale

\[ \mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho) \]

where \( \rho \) denotes the “ratio” of the contribution of modulus vs. anomaly mediation. We write the gaugino masses as

\[ M_a = M_s(\rho + b_ag_a^2) = \frac{m_{3/2}^2}{16\pi^2}(\rho + b_ag_a^2) \]

and \( \rho \to 0 \) corresponds to pure anomaly mediation.
Constraints on the mixing parameter

\[ m_{3/2} \text{ (TeV)} \]

\[ \tan \beta = 30 \quad \text{sign } \mu = 1 \quad m_t = 172 \text{ GeV} \]

- TACHYONS
- \( \tilde{\tau}_1 \) LSP
- \( m_h < 114 \text{ GeV} \)

ALLOWED

(Löwen, HPN, Ratz, 2006)
The “MSSM hierarchy problem”?

The influence of the various soft terms is given by

\[ m_Z^2 \simeq -1.8 \mu^2 + 5.9 M_3^2 - 0.4 M_2^2 - 1.2 m_{H_u}^2 + 0.9 m_{q_L}^{(3)} + \\
+ 0.7 m_{u_R}^{(3)} - 0.6 A_t M_3 + 0.4 M_2 M_3 + \ldots , \]
The “MSSM hierarchy problem”? 

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\[ + 0.7 m_{u_R}^{(3)} - 0.6 A_t M_3 + 0.4 M_2 M_3 + \ldots , \]

Mirage mediation improves the situation

- especially for small \( \rho \)
- because of a reduced gluino mass and a “compressed” spectrum of supersymmetric partners
  
  (Choi, Jeong, Kobayashi, Okumura, 2005)

- explicit model building required
  
  (Kitano, Nomura, 2005; Lebedev, HPN, Ratz, 2005; Pierce, Thaler, 2006; Dermisek, Kim, 2006)
Explicit schemes I

The different schemes depend on the mechanism of uplifting:

- uplifting with anti-D3 branes  
  \( \rho \sim 5 \) in the original KKLT scenario leading to  
  a mirage scale of approximately \( 10^{11} \) GeV

This scheme leads to “pure” mirage mediation:

- gaugino masses and  
- scalar masses

both meet at a common mirage scale.
Explicit schemes II

- uplifting via matter superpotentials
  
  allows a continuous variation of $\rho$
  
  leads to potentially new contributions for sfermion masses

- gaugino masses still meet at a mirage scale

- soft scalar masses might be dominated by modulus mediation

- similar constraints on the mixing parameter as in previous scheme

(Lebedev, HPN, Ratz, 2006)
Constraints on the mixing parameter

Below LEP

No EWSB

sign $\mu = 1$

$m_t = 175$ GeV

(V. Löwen, 2007)
Explicit schemes III

This “relaxed” mirage mediation is rather common for schemes with F-term uplifting

(Gomez-Reino, Scrucca; Dudas, Papineau, Pokorski; Abe, Higaki, Kobayashi, Omura;
Lebedev, Löwen, Mambrini, HPN, Ratz, 2006)

although “pure” mirage mediation is possible as well
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Main messages

predictions for gaugino masses are more robust than those for sfermion masses

mirage pattern for gaugino masses rather generic
The Gaugino Code

How can we test these ideas at the LHC?

Look for pattern of gaugino masses

Let us assume the

- low energy particle content of the MSSM
- measured values of gauge coupling constants

\[ g_1^2 : g_2^2 : g_3^2 \approx 1 : 2 : 6 \]

The evolution of gauge couplings would then lead to unification at a GUT-scale around \( 10^{16} \) GeV
Observe that
- evolution of gaugino masses is tied to evolution of gauge couplings
- for MSSM $M_a/g_a^2$ does not run (at one loop)

This implies
- robust prediction for gaugino masses
- gaugino mass relations are the key to reveal the underlying scheme

3 CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)
mSUGRA Pattern

Universal gaugino mass at the GUT scale

- mSUGRA pattern:
  \[ M_1 : M_2 : M_3 \approx 1 : 2 : 6 \approx g_1^2 : g_2^2 : g_3^2 \]

as realized in popular schemes such as gravity-, modulus-, gauge- and gaugino-mediation

This leads to

- LSP \( \chi_1^0 \) predominantly Bino
- \( \frac{M_{\text{gluino}}}{m_{\chi_1^0}} \approx 6 \)

as a characteristic signature of these schemes.
Anomaly Pattern

Gaugino masses below the GUT scale determined by the \( \beta \) functions

\[
M_1 : M_2 : M_3 \simeq 3.3 : 1 : 9
\]

at the TeV scale as the signal of anomaly mediation.

For the gauginos, this implies

- LSP \( \chi^0_1 \) predominantly Wino
- \( M_{\text{gluino}}/m_{\chi^0_1} \simeq 9 \)

Pure anomaly mediation inconsistent, as sfermion masses are problematic in this scheme (tachyonic sleptons).
Mirage Pattern

Mixed boundary conditions at the GUT scale characterized by the parameter $\rho$ (the ratio of anomaly to modulus mediation).

- $M_1 : M_2 : M_3 \approx 1 : 1.3 : 2.5$ for $\rho \approx 5$
- $M_1 : M_2 : M_3 \approx 1 : 1 : 1$ for $\rho \approx 2$

The mirage scheme leads to

- LSP $\chi_1^0$ predominantly Bino
- $M_{\text{gluino}}/m_{\chi_1^0} < 6$
- a “compressed” gaugino mass pattern.
String theory provides us with new ideas for particle physics model building, leading to concepts such as

- Local Grand Unification
- Mirage Mediation and a compressed SUSY spectrum

Geometry of extra dimensions plays a crucial role:

- localization of fields on branes,
- presence of warped throats

LHC might help us to verify some of these ideas!